ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Computer Science 8 (2012) 273 – 278
Procedia Computer Science

New Challenges in Systems Engineering and Architecting
Conference on Systems Engineering Research (CSER)
2012 – St. Louis, MO
Cihan H. Dagli, Editor in Chief
Organized by Missouri University of Science and Technology

Engineering Systems Thinking: Cognitive Competencies of Successful Systems Engineers

Moti Frank[a]*

HIT-Holon Institute of Israel, 52 Golomb St., Holon 58102, Israel

Abstract

Systems thinking is what makes systems engineering different from other kinds of engineering and is the underpinning skill required to do systems engineering. Engineering Systems Thinking is hypothesized as a major high-order thinking skill that enables individuals to successfully perform systems engineering tasks. First, several SE competency models are presented. Then, the CEST (Capacity for Engineering Systems Thinking) Competency Model is discussed. The model presents list of cognitive competencies that are all related to systems thinking and each one of them can be assessed separately. This paper discusses these cognitive competencies of successful systems engineers.

Keywords: Systems Thinking; Engineering Systems Thinking; CEST (Capacity for Engineering Systems Thinking); Competency Model; Cognitive Competencies

1. Introduction: Systems Thinking and CEST

Systems thinking is what makes systems engineering different from other kinds of engineering and is the underpinning skill required to do systems engineering” (Beasley & Partridge, 2011). *Systems thinking*, according to Senge (1994), is a discipline for seeing wholes. *Engineering Systems Thinking* is hypothesized as a major high-order thinking skill that enables individuals to successfully perform systems engineering tasks (Frank, 2000; 2002). Systems engineers need a systems view or a high capacity for engineering systems thinking (CEST) to successfully perform the roles of a systems engineering. Research found that this ability is a consistent personality trait, and that it can be used to distinguish between individual engineers (Frank, 2006). CEST may be developed through experience, education and training (Davidz & Nightingale, 2008; Kasser, 2011) and can be assessed (Frank, 2010). Moreover, well designed and taught systems engineering courses may accelerate the systems thinking development.

doi:10.1016/j.procs.2012.01.057

2. Systems Engineering Competency Models

What is required from successful systems engineers (the characteristics of successful systems engineers) is commonly called 'competencies of successful systems engineers' and much activity to develop systems engineering competency models has been done in recent years. A summary of several models is presented below.

2.1 INCOSE UK SE Competencies Framework

According to the systems engineering competencies framework of the United Kingdom chapter of the International Council on Systems Engineering (INCOSE UK, 2010), systems engineering ability comprises four key elements: competencies, basic skills and behaviors, supporting techniques and domain knowledge. The competencies are grouped into three categories: systems thinking, holistic lifecycle view and systems engineering management. The full document presents the following information for each competency: a description, why it matters and effective indicators of knowledge and experience in four levels – awareness, supervised practitioner, practitioner and expert.

2.2 MITRE Systems Engineering Competency Model

The MITRE competency model (Metzger & Bender, 2007) consists of 36 competencies organized into five sections: enterprise perspectives, systems engineering life cycle, systems engineering planning and management, systems engineering technical specialties, collaboration and individual characteristics. For example, the section 'enterprise perspectives' consists of 3 competencies - comprehensive viewpoints, innovative approaches and foster stakeholder relationships and the section 'collaboration and individual characteristics' consists of 9 competencies - building trust, building a successful team, communicating with impact, persuasiveness and influence, facilitating, managing, and championing change, high quality standards, results orientation, adaptability and integrity.

2.3 Systems Thinking Enablers

According to Davidz and Nightingale (2008), the primary mechanisms that enable systems thinking development include: experiential learning, a supporting environment and certain individual characteristics such as thinking broadly, curiosity, questioning, open-minded, communication, tolerance for uncertainty, strong interpersonal skills, and thinking out of the box.

2.4 Characteristics of the Ideal Systems Engineer

Burk (2008) found that the characteristics of the ideal systems engineer are: systems outlook, customer/user/consumer orientation, inquisitiveness, intuition, discipline, communication and cooperation (but not capitulation).

2.5 Other Competency Models

Other systems engineering competency models found in the literature include:

- Advancing the Practice of Systems Engineering at JPL (Jansma and Jones, 2006)
- NASA Systems Engineering Competencies (NASA, 2009).
- Systems Engineering Competency Taxonomy (Squires et al., 2011).
- Generic Competency Model (Armstrong et al., 2011).

3. The Maturity Model Framework

The maturity model for the competency of systems engineers is based on an assessment of an individual's skill against ability in each of three broad dimensions – knowledge (systems engineering and domain), cognitive characteristics (systems thinking and critical thinking) and individual traits (Kasser & Frank, 2010). The maturity model is a two-dimensional model. The vertical dimension covers three areas - knowledge of systems engineering and the application domain in which the systems engineering is being applied**,** cognitive characteristics and individual traits. The horizontal dimension is based on Kasser, Hitchins and Huynh (2009) who argue that anecdotal evidence exists for five types of systems engineers. The maturity model may serve both as a competency model and a framework for assessing/comparing other competency models (Kasser et al., 2011).

4. The CEST Competency Model

By reviewing the competency models presented earlier it seems that none of them refers to systems thinking as a thinking skill that composed of elements which each one of them can be assessed separately. The CEST Competency Model presents list of cognitive competencies that are all related to systems thinking and each one of them can be assessed separately. A prior study has identified 83 competencies of successful systems engineers (Frank, 2002; 2006). Later, These 83 were aggregated into thirty-five competencies – sixteen cognitive competencies, nine skills/abilities, seven behavioural competencies and three related to knowledge and experience (Frank, 2010). This paper focuses on the sixteen cognitive competencies.

5. The Cognitive Competencies of Successful Systems Engineers

The sixteen cognitive competencies that have been found in above-mentioned studies are as follows. Successful systems engineers:

1. **understand the whole system and see the big picture** - successful systems engineers understand the whole system beyond its elements, sub-systems, assemblies and components, and recognize how each element/sub-system/assembly/component functions as part of the entire system. They are multifaceted, able to consider issues from a wide range of perspectives and points of view and possess a generalist's perspective.
2. **understand interconnections** – successful systems engineers understand the interconnections and the mutual influences and interrelations among system elements. Systems thinking involves thinking about the system's interactions, interrelationships, and interdependencies of a technical, social, socio-technical or multi-level nature.

3. **understand system synergy** (emergent properties) - successful systems engineers are able to derive the synergy of a system from the very integration of the subsystems under their responsibility and are able to identify the synergy and emergent properties of combined systems.
4. **understand the system from multiple perspectives** - successful systems engineers avoid adopting a one-dimensional view. They are able to describe a system from all relevant perspectives that go beyond the mere engineering level.
5. **think creatively** - successful systems engineers are capable of creative-lateral-divergent-heuristic thinking in the raising-ideas stages of a project, and logic-convergent-algorithmic-analytical thinking in the implementation stages. They are able to offer workable creative/innovative original solutions, and transform a creative concept into a realizable idea. They are able to think outside the box, have unusual ideas and innovative thoughts, and are able to put things together in new and imaginative ways.
6. **understand systems without getting stuck on details**; tolerance for ambiguity and uncertainty - successful systems engineers are able to conceptually and functionally understand the system, even without understanding all its minutiae. Such engineers feel comfortable with ambiguity and working in unclear conditions and uncertain environments; not knowing all the details does not disturb them or hinder their efforts to solve a systems problem.
7. **understand the implications of proposed change** - successful systems engineers understand the system as a whole, are able to analyze the impact of proposed changes and are capable of anticipating and dealing with all implications of changes in the system.
8. **understand a new system/concept immediately upon presentation** - successful systems engineers understand and are able to describe the operation, purposes, applications, advantages, and limitations of a new system/idea/concept immediately after receiving an initial explanation.
9. **understand analogies and parallelism between systems** - successful systems engineers are able to compare and draw parallels between different disciplines. They are able to learn, infer, and draw conclusions from one discipline and apply these conclusions to another discipline.
10. **understand limits to growth** – when successful systems engineers are asked to indicate possible ways for improving performance they take into account factors and processes limiting and balancing the performance growth.
11. **ask good (the right) questions** - successful systems engineers constantly question the information they are given; this ability to ask good questions is a managerial tool that helps to avoid oversights and enables the asker to see the whole systems picture.
12. **(are) innovators, originators, promoters, initiators, curious** - successful systems engineers are curious and open-minded, and usually have broad interests, beyond the limited area of their expertise. They are willing to cope with (new) areas outside their area of expertise. They are constantly on the watch trying to determine what else can be done and where additional/new opportunities may emerge.

13. **are able to define boundaries** - successful systems engineers know how to set up proper boundaries and allocate tasks to the various teams, departments, partners and different contractors in such a way that each of them finds it possible to cope with their assigned tasks.
14. **are able to take into consideration non-engineering factors** - successful systems engineers are aware that, when preparing proposals or designing solutions, one must bear in mind non-engineering considerations such as ecological/environmental, marketing, "political", organizational, economical, personal issues, personality styles, business, re-use opportunities and different viewpoints.
15. **are able to "see" the future** - successful systems engineers are able to forecast and foresee the future. They have a sense of vision and are able to imagine how an organization, system, and industry will be developed in the future, and thus, to plan accordingly. They are able to take a macro view of the entire domain, not just the specific minutiae of the immediate domain.
16. **are able to optimize** - successful systems engineers understand optimization considerations and decide when to trade-off and compromise in three dimensions – engineering, cost and schedule, and operational.

6. Summary

This paper presents several current systems engineering competency models. The already published SE competency models include the INCOSE UK SE Competencies Framework, MITRE Systems Engineering Competency Model, Systems Thinking Enablers, Advancing the Practice of Systems Engineering at JPL, Characteristics of the Ideal Systems Engineer, NASA Systems Engineering Competencies, Systems Engineering Competency Taxonomy, Generic Competency Model and the Maturity Model Framework. However, none of these models refer to systems thinking as a thinking skill that composed of elements which each one of them can be assessed separately. The CEST Competency Model presents list of cognitive competencies that are all related to systems thinking and each one of them can be assessed separately. A prior study has identified 83 competencies of successful systems engineers. Later, These 83 were aggregated into thirty-five competencies – sixteen cognitive competencies, nine skills/abilities, seven behavioural competencies and three related to knowledge and experience. This paper discusses the 16 cognitive competencies. The list of the 16 cognitive competencies can be used as a basis for developing systems engineering courses and education programs, systems thinking assessment tool and systems engineering selection and placement processes and methods.

References

Armstrong, J.R., Henry, D., Kepcher, K., & Pyster, A. (2011). Competencies required for successful acquisition of large, highly complex systems of systems. Paper presented at IS 2011. Denver, CO. June 20-23, 2011.

Beasley, R., & Partridge, R. (2011). The three T's of systems engineering – trading, tailoring, and thinking. Paper presented at the 21st Annual Symposium of the International Council on Systems Engineering (INCOSE). Denver, CO, USA. June 20-23, 2011.

Burk, R.C. (2008). Systems engineering in professional practice. In: G.S. Parnell, P.J. Driscoll & D.L. Henderson (Eds.). *Decision Making in Systems Engineering and Management*. Hoboken, NJ: John Wiley & Sons.

Davidz, H.L., & Nightingale, D.J. (2008). Enabling systems thinking to accelerate the development of senior systems engineers. *INCOSE Journal of Systems Engineering*, vol. 11, no. 1, pp. 1-14.

Frank, M. (2000). Engineering systems thinking and systems thinking. *INCOSE Journal of Systems Engineering,* vol. 3, no. 3, pp. 163-168.

Frank, M. (2002). Characteristics of engineering systems thinking – A 3-D approach for curriculum content. *IEEE Transaction on System, Man, and Cybernetics*, vol. 32, no. 3, Part C, pp. 203-214.

Frank, M. (2006). Knowledge, abilities, cognitive characteristics and behavioral competences of engineers with high Capacity for Engineering Systems Thinking (CEST). *INCOSE Journal of Systems Engineering,* vol. 9, no. 2, pp. 91-103.

Frank, M. (2010). Assessing the interest for systems engineering positions and other engineering positions' required capacity for engineering systems thinking (CEST). *INCOSE Journal of Systems Engineering,* vol. 13, no. 2, pp. 161–174.

INCOSE UK (2010). INCOSE UK Systems Engineering Competencies Framework. Retrieved June 24, 2011 from http://www.incose.org/members/index.aspx

Jansma, P. A., & Jones, R. M. (2006). Systems Engineering Advancement (SEA) Project. Retrieved June 24, 2011 from

http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/38979/1/05-3271.pdf

Kasser, J.E., Hitchins, D., & Huynh, T.V. (2009). Reengineering Systems Engineering. Paper presented at the 3rd Annual Asia-Pacific Conference on Systems Engineering (APCOSE), Singapore, 2009.

Kasser, J.E., & Frank, M. (2010). A Maturity Model for the Competency of Systems Engineers. Paper presented at the 20th Anniversary INCOSE (International Council on Systems Engineering) Symposium (INCOSE 2010), Chicago, USA, 12-15 July 2010.

Kasser, J. (2011). Systems engineering a 21st century introductory course on systems engineering. *INCOSE Journal of Systems Engineering* (in press).

Kasser, J.E., Hitchins, D., Frank, M., & Yang Yang Zhao (2011). A framework for competency models of systems engineers. *INCOSE Journal of Systems Engineering* (in press).

Metzger, L.S., & Bender, L. R. (2007). MITRE Systems Engineering Competency Model. Retrieved June 24, 2011 from

http://www.mitre.org/work/systems_engineering/guide/10_0678_presentation.pdf

NASA (2009). Systems engineering competencies. Retrieved June 24, 2011 from:http://www.nasa.gov/pdf/303747main_Systems_Engineering_Competencies.pdf

Senge, P. (1994). The fifth discipline: The art and practice of the learning organization. New York, NY: Doubleday.

Squires, A., Wade, J., Dominick, P., & Gelosh, D. (2011) Building a competency taxonomy to guide experience acceleration of lead program systems engineers. Paper presented at CSER 2011, University of Southern California, April 15-16.